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To cite this article: N A Abaimov *et al* 2019 *J. Phys.: Conf. Ser.* **1261** 012001

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Investigation of hydrodynamic features in two-stage steam-air-blown entrained-flow gasifier

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Abstract. The goal of the work is to study the hydrodynamics features of media movement in IT SB RAS two-stage steam-air-blown entrained-flow gasifier. Analysis of the data obtained using the verified CFD model based on the results of the experiments showed that the conversion process in the mode proceeds in three phases, the localization of which depends on the input mode and design parameters. According to the results of CFD modeling, the injection of relatively cold, weakly superheated steam axial jet into second phases creates hydrodynamic, structural and temperature heterogeneity, which decreases markedly in the third phases. The supplied steam at the second phase performs mainly the functions of a cooler, causing a decrease in the temperature of the reaction mixture and a decrease in the rate of gasification reactions.

1. Introduction

The development of coal gasification technologies is associated with the rapid depletion of gaseous (natural gas) and liquid (oil) fossil fuels. Using gasification of coal, it is possible to produce synthesis gas (syngas) used in the power industry as a fuel for integrated gasification combined-cycle plants (IGCC) [1] and in the chemical industry as a raw material for the production of synthetic substances. Syngas for the chemical industry is usually produced in oxygen-blown gasifiers to eliminate nitrogen from the syngas. If syngas is intended for power industry (IGCC), then it can also be produced in air-blown gasifiers, since nitrogen is not a problem [2]. Air-blown gasifiers do not need oxygen, so IGCC with them do not have a high-cost air separation unit (ASU) [3].

In order to suppress nitrogen oxides [4] or for the shift-process (pre-combustion IGCC), it is advisable to carry out steam-air-blown gasification, which allows increasing the H_2/CO ratio in the syngas. It is obvious that for carrying out steam-air-blown gasification more heat is required, which in this case can be obtained, for example, with highly heated blast air [5]. Air-blown gasification on an industrial scale is carried out only in two-stage gasifiers like Mitsubishi Heavy Industries (MHI) [6]. Two-stage gasifiers have a relatively complex hydrodynamics of media movement, especially if they have a stream of steam.

An installation with a capacity of 1 MW has been constructed for the study of steam-air-blown gasification in the Kutateladze Institute of Thermophysics SB RAS, Novosibirsk, Russia (IT SB RAS) [7]. The gasifier is characterized by a curvilinear trajectory of coal movement, complicated by the interaction with the steam jet, therefore, to analyze the obtained experimental data, it is necessary to study the hydrodynamics features of media movement in the installation. Traditionally, to solve such problems researchers use the method of computational fluid dynamics (CFD) [8].



The goal of the work is to study the hydrodynamics features of media movement in IT SB RAS two-stage steam-air-blown entrained-flow gasifier.

2. Methods

2.1. Experimental gasifier

Experimental studies were performed on an IT SB RAS gasifier with a capacity of 1 MW (Fig. 1), which is a modification of the famous gasifier of the IT SB RAS with a capacity of 5 MW [9]. The design of the gasifier has two different stages. In the combustion chamber (swirler) occurs burning in the oxygen zone. In the gasification chamber occurs coal gasification by combustion products and steam of char (flying out of the swirler).

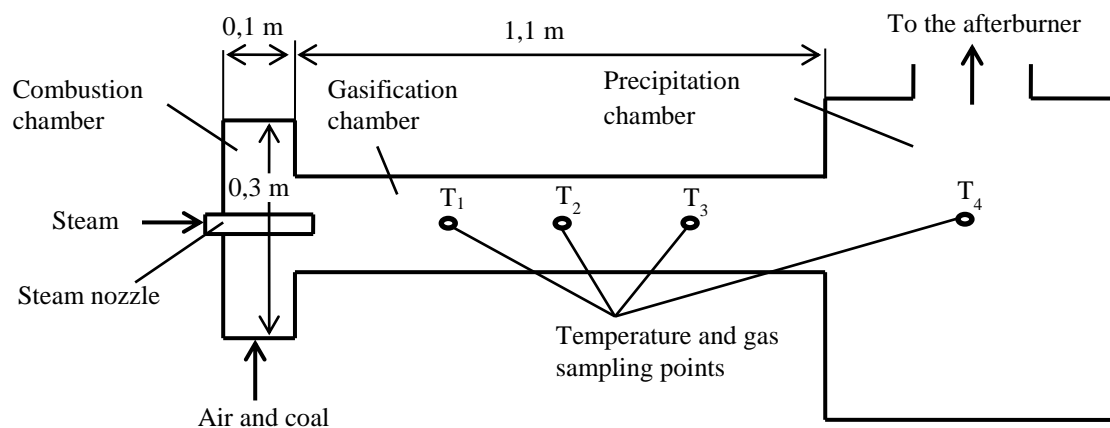


Figure 1. The scheme of experimental gasifier.

The experiments were carried out with the use of oxidized bituminous Kuznetsk coal grade D ROKI. Coal is converted at a flow rate of 20 kg/h under severe thermodynamic conditions: with cold air supply (15°C) with a flow rate of 90 Nm³/h and steam (200-250°C) with a flow rate of 10 kg/h [7]. Heat loss through brickwork was about 10-30%. To be able to work in the autothermal mode without inlet flows heat additives, the reactivity of the coal is increased by mechanically activating it in a disintegrator-type mill. The maximum particle size determined by the optical-digital method does not exceed 70 μm.

2.2. Calculating model

To study the hydrodynamics of a gasifier, a previously developed CFD model is used, detailed described in [10, 11]. The verification of this model according to the data of this experiment is given in section 3.

3. Results and discussion

The results of CFD-calculation are shown in Figure 2. The calculated lines are quite close to the experimental points. It indicates the applicability of the model for solving such problems. The discrepancies can be caused by the fact that the experimental data are taken from the point, and the calculated data are averaged over the cross section.

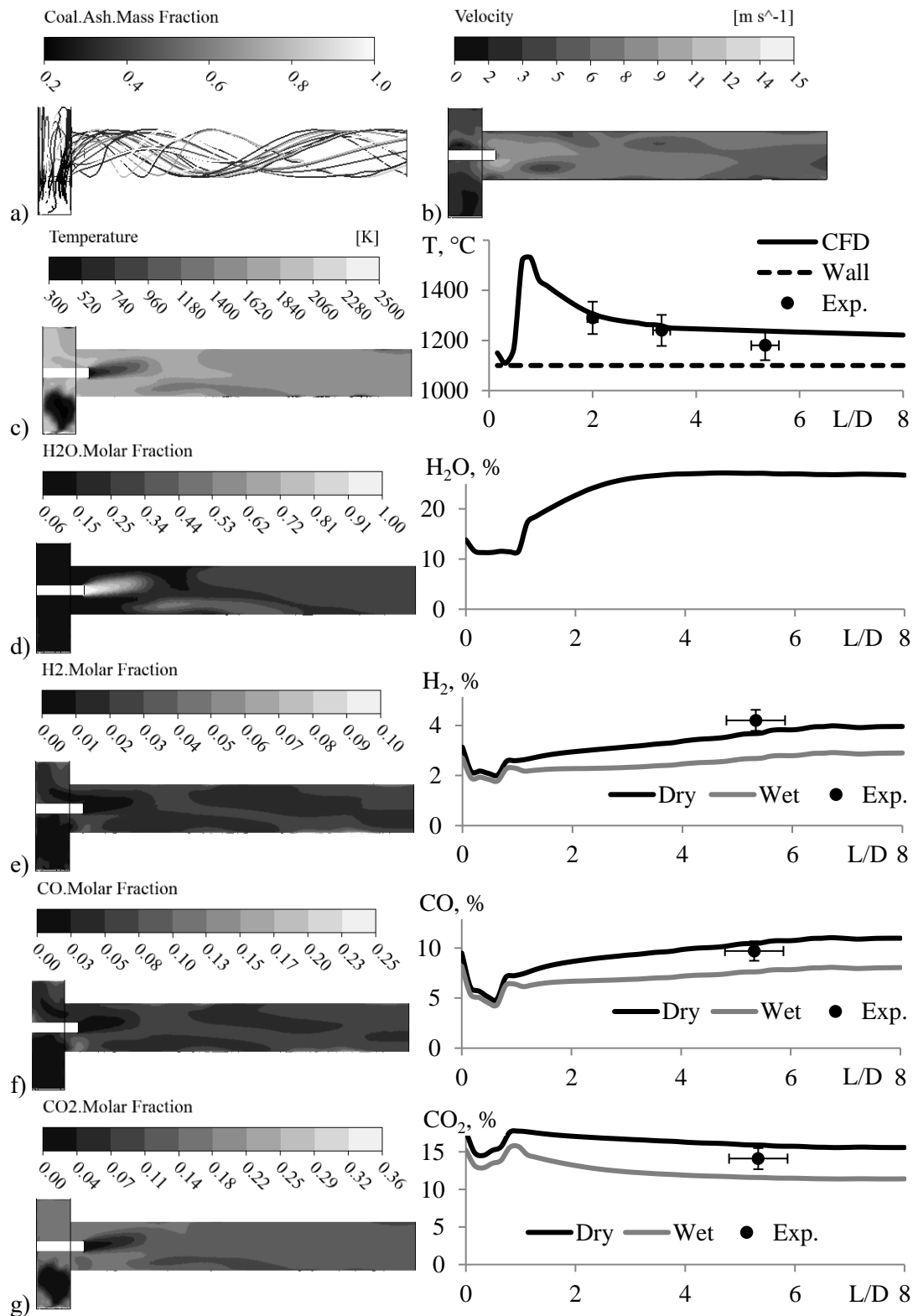


Figure 2. Results of CFD simulation: distribution fields in the longitudinal section and graphs of averages values over the cross section along the length of the gasifier: a) the trajectory of coal movement and ash mass fraction in coal; b) gas velocity; c) temperature; d) H₂O (vol.); e) H₂ (vol.); f) CO (vol.); g) CO₂ (vol.).

Analysis of the obtained data shows that the conversion process in the mode proceeds in three phases, the localization of which is determined by the input parameters:

1) Coal combustion in a swirling air flow. This phase, confined to the oxygen zone with a length of ~ 1 caliber (1 L/D), is localized mainly in the combustion chamber, and is characterized by the maximum irregularity of temperatures (about 2200°C) and gas concentrations over the cross section of the combustion chamber. This is explained by the presence in the swirler of the inlet nozzle that supplies the cold (15°C) fuel-air mixture and the stagnant zone with a maximum temperature (2200°C) and concentrations in which the coal dust is for a long time due to the vortex motion. After the combustion chamber, the mixture of gases and partially reacted fuel enters the gasification chamber, where the subsequent phases of the conversion proceed.

2) Gasification of partially reacted coal in a peripheral vortex with gases from a swirler. The process develops in the first half of the gasification chamber (1-4 calibers), where the flow from the swirler continues to spread along the chamber walls, practically without mixing with the central steam jet, which maintains between them a large temperature difference (about 1800°C) and gas concentrations (especially H₂O). The presence of incompletely reacted coal at this site, combustion products (H₂O and CO₂) and temperatures sufficient for gasification reactions (above 1300-1400°C) leads to a sharp rise in the concentration of combustible components of synthesis gas (H₂ and CO). Due to heat and mass transfer with the steam jet, wall and endothermic reactions, the temperature of the vortex peripheral flow drops, and the conversion proceeds to the final phase.

3) Homogeneous reaction (water gas shift reaction, WGSR) of the gas mixture with the steam supplied through the nozzle. In the second half of the gasification chamber (4-8 calibers), the average over the cross section temperature of the mixture drops below 1300-1400°C, as a result of which heterogeneous reactions practically cease and the composition of the syngas begins to be determined by the course of WGSR. The irregularity of temperatures (400-500°C) and the concentration of the components of the syngas over the cross section of the gasification chamber is minimal due to the relatively high mixing degree of the steam jet and the flow from the swirler.

The second and third phases of conversion are directly related to the interaction of the steam jet from the nozzle and the dust and gas flow leaving the combustion chamber. The interaction is characterized by the presence of hydrodynamic, structural and temperature heterogeneities in the gasifier reaction chamber (Fig. 3).

The gasification chamber has a complex organization of the media movement with hydrodynamic flow separation (peripheral flow from the combustion chamber and axial jet of steam), which resembles the work of the gasifier investigated in [12]. However, unlike these works, where gasifier was considered with heating axial flow of combustion products and heated peripheral flow of gasified coal, here a peripheral vortex acts as a heating flow, and the heated medium is an axial steam jet. The latter combination is often encountered in the structural design of fur-burner apparatus and chemical reagents input units into gasifiers.

Hydrodynamic heterogeneity is expressed in the helical peripheral movement of a heterogeneous system with a gradually increasing longitudinal step from 2 to 4 calibers (Fig. 3a).

Structural heterogeneity of the flow is maintained at a distance of 3-4 calibers from the combustion chamber (Fig. 3b). The swirler design asymmetry leads to asymmetry, instability, and nonstationarity of the vortex in space and time, which increases the intensity of mixing the peripheral flow from the swirler and the steam jet from the nozzle. The steam supplied along the axis pulls up to the peripheral vortex and at a distance of 2 calibers from the combustion chamber begins to move into tangled motion.

The temperature heterogeneity of the flow is manifested at a distance of 3-4 calibers from the combustion chamber (Fig. 3c). On it, the temperature of the axial steam jet rises from 200 to 1000°C, and the temperature of the peripheral flow decreases from 1500 to 1200°C. Heating the steam jet is associated with its expansion almost 3 times, with an increase in the volume occupied by the steam and a longitudinal pitch of the vortex. As a result, in the third phase, heterogeneities are substantially reduced.

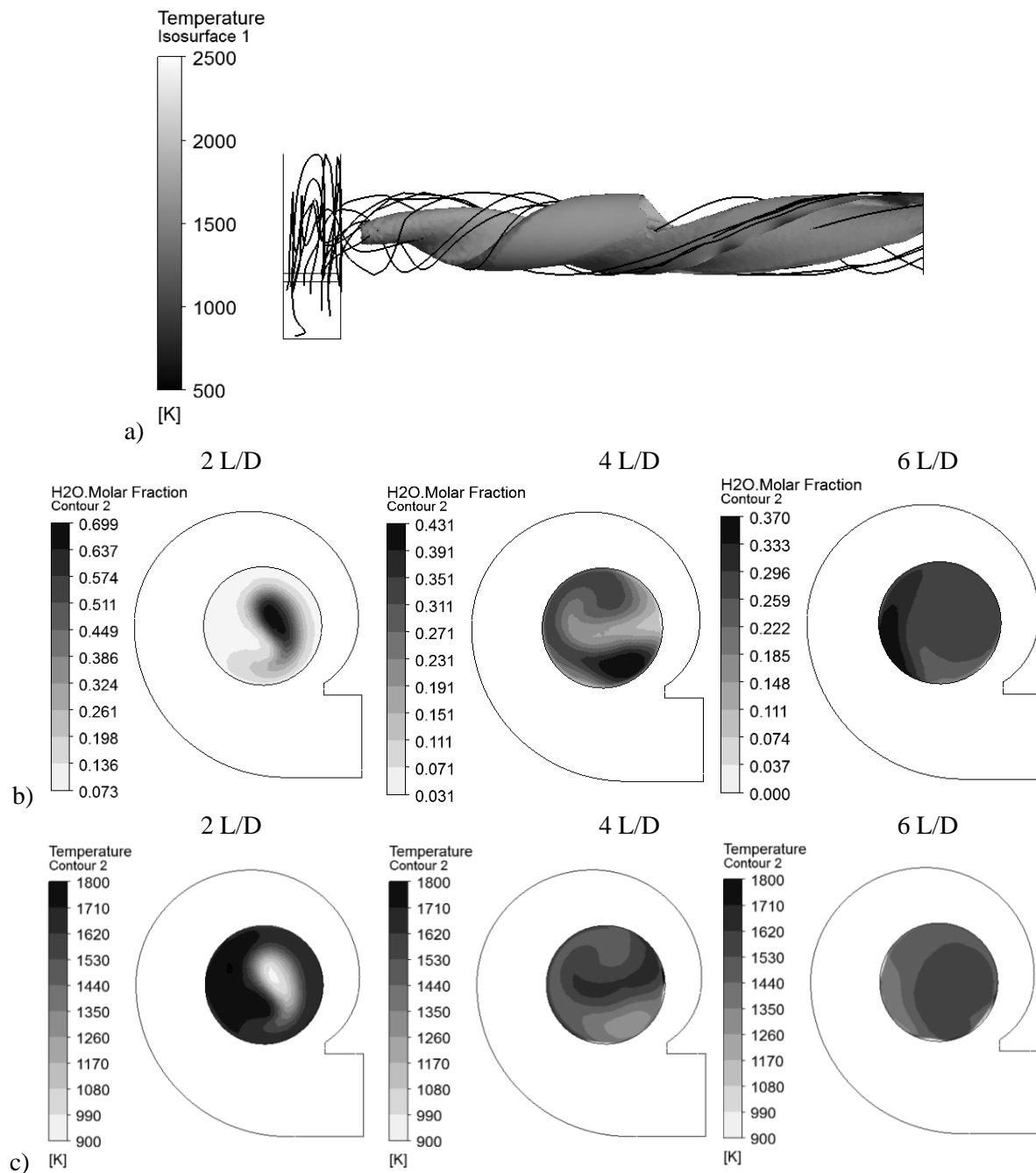


Figure 3. The heterogeneity of the mixture: a) hydrodynamic (isosurface with a fraction of steam $H_2O = 30\%$ (vol.) and the trajectory of coal particles); b) structural; c) temperature.

The given fields of concentration and temperature distributions indicate a complex non-uniform nature of the dynamics and distribution of the studied parameters. It is a factor that complicates experimental studies, but increases their significance.

4. Conclusion

Analysis of the data obtained using the verified CFD model based on the results of the experiments showed that the conversion process in the mode proceeds in three phases, the localization of which depends on the input mode and design parameters:

- 1) Coal combustion in a swirling air flow (0-1 caliber).

2) Gasification of partially reacted coal in the peripheral vortex of gases from the swirler (1-4 calibers).

3) Homogeneous reaction of a mixture of gases with steam supplied through a nozzle on WGSR (4-8 calibers).

According to the results of CFD modeling, the injection of relatively cold, weakly superheated steam axial jet into second phases creates hydrodynamic, structural and temperature heterogeneity, which decreases markedly in the third phases. The supplied steam at the second phase performs mainly the functions of a cooler, causing a decrease in the temperature of the reaction mixture and a decrease in the rate of gasification reactions.

In future work, it is planned to study one- and two-stage gasification of mechanically activated various degrees of metamorphism coals with optimization of the thermal and aerodynamic experiment parameters, as well as the issues of including the considered node into the work of a full-scale gasifier.

Acknowledgements

The work was supported by Act 211 Government of the Russian Federation, contract № 02.A03.21.0006.

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